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Star formation in galaxies

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Abstract The present work aims at reviewing the basic problems associated with the currently understood mechanism of star formation in galaxies. Stars are born out of gas and dust pervading the interstellar medium. How this raw material spreads over the interstellar space with spotty distribution and transforms through various physical and dynamical processes into mysterious stars has been discussed here. Molecular clouds are the most favourable places for star birth. The mechanism for formation of interstellar clouds along with physics and chemistry of molecular clouds have been included in our discussions.

Sir James Jeans showed that the cosmic gas clouds suffer gravitational instability when its dimension and mass exceed some critical values. We have explained here the physics of gravitational collapse of gas cloud and deducted mathematically Jean's critical length and mass for gravitational collapse. Collapse enhances cloud density. We have shown mathematically how the interior of a collapsing cloud fragment into pieces and produce a number of separate gas blobs within the parent cloud. Each separate gas blob within the collapsing cloud continues to be fragmented into smaller and smaller pieces. The entire process of this repeated fragmentation of the cloud proceeds isothermally until the density of the individual fragment attains a critical value. The fragmentation is halted when the fragments start becoming opaque to low frequency radiation. This phase is followed by slow adiabatic contraction gradually increasing the opacity and capturing the higher frequency radiation. Opacity helps them to raise their temperature gradually until they are able to aquire temperature sufficient to generate hydrogen fusion within their centres. They are then transformed into fully developed shinning stars imbedded within the parent gas cloud. It is emphasized that these tiny gas bolbs created by fragmentation gather mass either by accreting mass from the surrounding gas cloud or by colliding with other gas blobs in their neighbourhood. We have given an estimate of the minimum and maximum mass of a star in this connection. We have discussed the concept of the initial mass function (IMF) of the stars formed and the star formation efficienty (SFE) of a gas cloud. Process of evolution of star formation efficiency of a gas cloud has also been included in our work.

We have described how the density, temperature, turbulent motion and magnetic field of a gas cloud influence the star formation rate. Magnetic field has a complex role in the process of star formation which has been discussed in details.

Finally, we discuss the formation of substellar objects better known as brown dwarfs which are formed in the same event, and assess the contribution of these brown dwarfs to the baryonic dark matter that is believed to pervade the galaxies and the universe.

Keywords : Molecular clouds, gravitational collapse, star formation

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Plan of the Article

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1. Introduction

The problem of star formation from interstellar gas clouds in galaxies has drawn keen attention of many astronomers during the last couple of decades. Observations and analysis of the various physical and dynamical properties of stars clearly indicate that they are of different ages. In fact, the positions of stars in the Hertzsprung-Russell diagram can be interpreted as the footprints of stars with different masses and chemical compositions in course of their evolution in time. The colour-magnitude diagrams of galactic clusters in our Galaxy bear unmistakable evidences that these clusters have formed all the time from early phase of the disk formation of the Galaxy till very recently. Careful analysis of the photographic plates of nebulae in galaxies also bear testimony to the fact that stars form in groups within massive clouds of interstellar gas by gravitational collapse and subsequent fragmentation. Spiral arms of galaxies are heavily populated by blue hot stars which are of more recent origin. So star formation in a galaxy like our own appears to be a continuous process. It is therefore natural that astronomers have turned their attention to understand this very important aspect of the galactic drama. In the following sections, we have tried to develope the understanding of the problem of star formation out of the interstellar gas.

2. Interstellar matter

The raw materials used for star formation are the interstellar gas and dust which together is known commonly as the interstellar matter. The space between the stars in any galaxy is filled with irregular and patchy distribution of interstellar matter comprising of a higher density component directly visible as bright and dark nebulae and a relatively low density component which is not directly visible. The gas and dust content being higher in spiral galaxies like our own and in irregular galaxies like the Magellanic Clouds compared to that in elliptical galaxies, the spottiness of the distribution of interstellar matter is more spectacular and pronounced in spiral and irregular galaxies than in the ellipticals. In fact, the spiral arms present a grand display of the irregular distribution of both hot and cool gas mixed with dust particles.

Irregularities are also common in the distribution of the tenuous and low density invisible component of the interstellar matter. This is revealed in two ways. First, the dust particles mixed in gas dim the light coming from distant stars by absorption. This absorption is observed to possess directional dependence. Early observers emphasized that the general absorption was not uniform throughout the Galaxy. The extensive photometric measurements of the selective extinction of distant *O* and *B* stars show that—"The absorption in the Galaxy is obviously so irregular and spotted that a constant coefficient cannot be used for any large region of space". Trumpler [1] in his classical paper describing the results of observations of distant galactic clusters emphasized that the absorption of light was not uniform throughout the Galaxy and that the distribution of absorbing materials had local irregularities. Secondly, the multiple lines of Ca II observed in the spectra of distant hot stars clearly indicate that the interstellar gas mostly exists in discrete clouds. Each cloud moves in space with its own characteristic velocity producing its own Doppler shift in the spectrum of the background star. Work on the interstellar Ca II lines by many astronomers demonstrated conclusively that the lines originate in discrete clouds which swin in the interstellar space with random velocities, superimposed on their motions due to galactic rotation [2–4]. Large-scale local variations of gas density as revealed by optical observations were soon confirmed also by radio observation at 21 cm wavelength of hydrogen radiation [5–6]. 21 cm observations also revealed the existence of large cloud complexes in local regions otherwise invisible. All these observations therefore can be summerized to propose a model for distribution of the interstellar matter (gas and dust) as follows :

(a) A more tenuous and almost uniform distribution of mater pervades the entire region of the galactic plane This component mainly participates in the galactic rotation.

(b) Superimposed on this nearly uniform component there are clouds of various dimensions and densities which possess sufficiently varied random velocities over and above their motions due to galcatic rotation

3. Interstellar clouds

In this section, we briefly summarise the mechanisms for the formation of interstellar clouds which are progenitors of new generations of stars. The general picture of the density variation of the interstellar medium is understood in terms of clouds embedded in a tenuous intercloud medium. On the other hand, difficulties are encountered to understand the concept of a cloud because clouds appear hierarchically clumped [7], and structures exist on a variety of scales in each cloud. Even the concept of a cloud boundary is difficult to define. Some diffuse clouds appear as local concentrations on the periphery of giant molecular clouds [8] and some giant molecular clouds form the cores of larger atomic clouds [9] This hierarchy of structures implies that any particular cloud may have several formation mechanisms. However, three principal processes appear to be the most important for imparting the cloudy structures to the interstellar matter These are :

(1) interstellar shocks that compress the ambient gas into shells, supershells and filaments;

(2) Cloud-Cloud collisions building larger clouds from smaller clouds, and

(3) instabilities of various kinds and of various lengths propagating through the ambient gas. In this respect, Parker instability, thermal instability and gravitational instability are the most important.

Interstellar shocks are generated as a result of supernova explosions, large-scale galactic flows as in density waves, or strong winds from hot OB stars. That shells and supershells and also the filaments are layers behind shocks are corroborated from their swept up appearance and also by the fact that these regions show parallel magnetic field alignment. A collision between two non-magnetic clouds may either build up a larger cloud or may also destroy the clouds. The exact outcome will depend on their relative sizes, densities, velocities, and on the impact parameter of the collision. The pioneering work was done by Kahn [10] and further work was carried out later by others [11,12]. Magnetic collisions are more cohesive because the field lines of both the clouds may be mutually entangled, thus entangling the clouds [13,14].

Cloud structures of various dimensions may also be formed out of the ambient medium by various types of instabilities driven in the interstellar gas. Thermal instabilities were investigated by several authors [15,16]. It has been found that some of the observed cloud structures could form during transitions between thermally stable phases of the different components of the interstellar gas such as molecular clouds, HI clouds and HII regions. The Parker instability [19] arises when a fluid layer of higher density is imposed on another fluid layer of lower density in the presence of a magnetic field. Thus, it is a magnetic Rayleigh-Taylor instability, and in the case of the interstellar gas, the magnetic buoyancy and the cosmic rays take the place of the lighter fluid while the interstellar gas itself plays the role of the heavier fluid. The characteristic length scale of such instability is $2\pi H$ where H is the scale height. Since the scale height of the galactic gas is a few hundred parsecs, very large cloud complexes can condense by Parker instability [20-22]. Lastly, gravitational instability seems to be inevitable in the galactic disk where local condensations are most common and magnetic field is present to remove the angular momentum from the condensations [23-25]. The length scales of gravitational instabilities are similar to those of the Parker instability and large cloud complexes may grow as a result. Gravitational instability may be operative simultaneously with other instabilities. The observed molecular cloud complexes along the rims of shells and supershells are the results of the gravitational instability driven in these objects [26-28].

4. Molecular clouds

Adams* was the first astronomer to detect molecules in the interstellar space. He identified in late 1930s and early 1940s optical absorption lines of CN, CH and CH^+ at wavelengths around 4000 Å in the spectra of some bright stars. In later years, radio astronomical techniques have mainly been used for detection and study of interstellar molecules because most of these molecules radiate at centimeter, millimeter and submillimeter wavelengths.

In 1963, hydroxyl radical (OH) was discovered by Barrett and coworkers. This radical emits at 1665 MHz (18 cm wavelength). Then starting from late 1960s, discovery of interstellar molecules gained momentum and many molecules have been identified in rapid succession during 1970s and 1980s. The number of molecules known at present has reached nearly one hundred mark. The discovery of OH was followed soon by identification of other radicals and polyatomic molecules such as ammonia (NH_3), water (H_2O) and formaldehyde (H_2CO) in 1968–69. Carbon monoxide (CO) was detected in 1970. This molecule emits strongly at 2.6 millimeter wavelength. The molecular hydrogen (H_2) was also discovered in 1970 by ultraviolet observations with a rocket borne telescope. H_2 is the most abundant molecule in space, but it is very difficult to observe because the far ultraviolet lines it emits are very efficiently absorbed by the dust particles in space. Because of this observational difficulty and because H_2 interacts very poorly with photons, it was not the first molecule to be detected inspite of its overwhelming abundance in interstellar space.

A large haul of molecules have been detected in the molecular cloud complex of Sagittarius B2 at the galactic centre region. In fact, Sagittarius B2 complex has become the most favourite forest for the molecule-hunting astronomers. Among the discovered species there are many complex organic molecules belonging to the class of alchohals like methyl Alchohal (CH_3OH), acids like Formic Acid (HCOOH), amides like Formamide (NH_2CHO) and amines like Methanimine (CH_2NH).

Although CO is only about 10^{-5} as abundant as H_2 molecules in interstellar space, it has served as the standard tracer of the molecular map for the entire galaxy by virtue of the fairly easy detectibility by its strong emission at 2.6 mm wavelength [29-34]. Molecular gas is observed to be present throughout the Galaxy, but there are conspicuous regions where it exists in clouds of much higher densities [35]. The greater part of the molecular gas is assembled in massive and large cloud complexes. These have been called giant molecular clouds (GMCs). The molecular clouds have masses in the range 10–10^7 $M_\odot$ with a power law mass spectrum of $n(m) \propto m^{-1.5}$ [27,36-40]. But GMCs are those that have masses in the range 10^5–10^7 $M_\odot$ with sizes of several tens of parsecs and average densities of $5\times10^2-10^4$ particles cm^{-3}. A GMC does not possess one single monolithic structure but is composed of multiple dense clumps of molecules under one envelope. The individual clumps are of average masses 10^3–10^4 $M_\odot$ and of average sizes 2–5 pc. The central densities of these clumps may be as high as 10^6 particles cm^{-3}. The molecular gas in the clouds is mixed with interstellar dust particles and is surrounded by clouds of neutral hydrogen. The dust particles act as a shield to protect the molecules against breaking by the impact of ultraviolet photons which pervade the interstellar space. The central temperatures in the

*W S Adams *Astrophys. J.* 93 11 (1941)

clouds are very low, usually in the range 10–20 K, the central densities being much higher than the average as mentioned above. The complexes are found in abundance in the nuclear region of the Galaxy and also in the region of a wide ring extending between 4 to 8 kpc from the centre of the Galaxy. The total mass of H_2 in cloud complexes may be as high as 5×10^{9} $M_\odot$ [41,42].

The giant molecular clouds are the most massive objects in the Galaxy. The prevailing conditions of low central temperature and high central density make them vulnerable to gravitational collapse and hierarchical fragmentation (Figure 1).

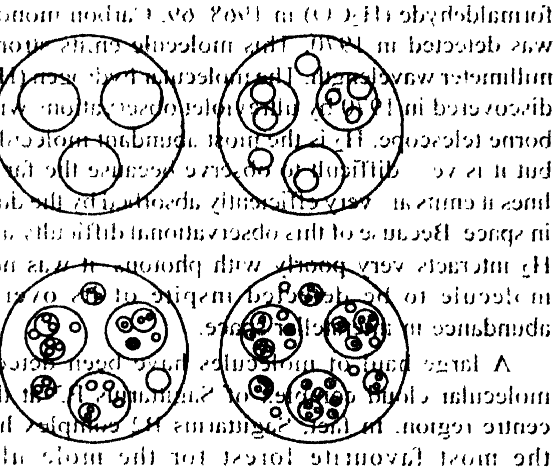

Figure 1. Schematic model of hierarchical fragmentation of a molecular cloud leading to the formation of a group of stars.

Molecular clouds have thus been identified as sites for formation of new generations of stars [41–46]. Groups of massive O and B stars and T Tauri stars are often found embedded in massive cloud complexes. That the low mass stars are also formed in large numbers in the same events is clearly indicated by isolated sources of strong infrared radiation measured within the cloud complexes. In this respect Rho Ophiuchi dark cloud serves as a typical example. Here star formation is going on right now. This cloud observed in the constellations of Ophiucus and Scorpius situated at a distance of nearly 250 pc covers a large area of the sky. Due to its nearness and convenient position, the cloud has been observed over the last two decades in minute details. The optical light is effectively screened by the existence of a thick distribution of dust. The details have been studied by observations in infrared and radio wavelengths. Studies have revealed the existence of more than a hundred young stars and six HII regions embedded in the veil of gas and dust within the cloud. More than ten percent of the gas in the cloud has already condensed into stars. Observational results indicate that 30 to 50 percent or even more of the gas in this cloud will finally condense into stars and a galactic cluster of stars will emerge out of this cloud [47–59].

Similar searches for young stellar populations have been conducted in λ Orionis region [60], Taurus dark clouds [61,62], Monoceros R2 [63], the Orion molecular clouds [64], the Chamaeleon dark clouds [65], the Serpens molecular cloud [66] and the NGC 2023/2024/2068/2071 complex [67]. Very young massive stars have been detected in λ Orionis and Monoceros complexes. There are several reflection nebulae and the very young galactic cluster NGC 2264 containing many early young stars and T-Tauri variables in the Monoceros Complex [63].

With the gradually improving sensitivity of the centimeter and millimeter wavelength receivers, it was realised that the less bright regions were too numerous compared to the more bright ones. It was also realised that these less bright sources were nothing but invisible young low-mass stars and further that the low-mass stars were formed in overwhelmingly large numbers compared to the high-mass stars associated with bright sources. The Infrared Astronomical Satellite (IRAS) sent in 1983 mapped the infrared point-sources spread over the sky. It was found that about half of these sources were associated with known dense cores in dark clouds. Many of these sources are associated with optically visible T-Tauri stars, but many more, previously unknown are believed to be the protostars younger than T-Tauri stars. Thus long years of

the dense cores in molecular clouds are the regions where protostellar formation is rather common and certain [68–70].

In the next section, we shall briefly discuss the physical characteristics of molecular clouds and analyse the conditions under which a cloud collapses and fragments giving birth to a group of stars.

5. Physics of Molecular Cloud Collapse

The basic physical process for star formation in dense cores of molecular clouds is the gravitational collapse. The cloud remains stable until the pressure at each point in the cloud can balance the gravitational pull. As soon as the balance is disturbed the cloud becomes unstable and starts collapsing. The collapse of a spherical cloud has been worked out in general. The cloud is massive ($M \sim 10^3$–10^6 $M_\odot$), dense ($\rho \sim 10^{-21}$–10^{-19} gm cm^{-3}, $n \sim 10^3$ to 10^5 cm^{-3}) and cold ($T \sim 10$ K at the centre), and is composed of molecular hydrogen with cosmic abundance (the mean molecular weight $\mu = 2.3\, m_H$).

For lowest densities, that is, below about 3×10^{-21} to 3×10^{-20} gm cm^{-3}, cosmic ray heating and CII cooling are the dominant processes. At densities higher than 3×10^{-20} gm cm^{-3}, cosmic ray heating and CII cooling become unimportant and the dominant processes become compressional heating and grain cooling. Dust grains are the most efficient coolant and opacity source for densities $\geq 10^{-18}$ gm cm^{-3}. The cloud will cool effectively by radiation in the far infrared where thermal emission by dust grains is most important. Far infrared and microwave transitions of abundant molecules will also be important cooling agents. At $\rho > 10^{-19}$ gm cm^{-3} the gas temperature becomes closely coupled to that of the dust grains [71]. Since the infrared emissivity of the dust varies as T_d^2, where T_d is the dust temperature, T_g depends only weekly on the density and the compressional heating rate, and also is not very sensitive to the amount or the composition of the dust. As a result, a dense collapsing cloud should continue to possess a fairly well determined temperature of the order of 10 K over the entire density range during the collapse — all way from the density ($\sim 10^{-19}$ gm cm^{-3}) at which collapse of the cloud on itself starts to the density ($\sim 10^{-13}$ gm cm^{-3}) at which the fragments become opaque to the infrared radiation from the dust grains [71–73].

As the cloud collapses on itself, the density increases everywhere within the cloud. Calculations show that the collapse is highly non-homologous, so the core collapses much faster than the outer region. As a result, the density increases at a much faster rate in the central region of the cloud. As the density within the cloud attains some critical value, of the order of 10^{-16} gm cm^{-3} [74], fragmentation within the cloud commences. By fragmentation is meant the development of the isolated subcondensations within the cloud which are gravitationally bound. These subcondensations again further collapse onto themselves leading to further fragmentation of each subcondensation (Figure 5). Several stages of fragmentation may thus occur leading finally to the formation of protostars of various masses. This process is known as *hierarchical fragmentation* of the cloud.

The collapse of the original cloud as well as of the individual fragments is *isothermal* initially at a prevailing average temperature of 10 K. The entire process remains isothermal so long as the compressional heat inside is radiated efficiently before it can build up inside the cloud, that is, so long as cooling remains efficient. This situation prevails as long as the cooling time, t_{cool} is less than the free-fall time, t_{ff}. Here, $t_{cool} = \frac{1.5\,KT}{n\Lambda}$ where Λ is the cooling rate and n is the number density of particles, K and T having usual meaning [75] and

$$t_{ff} = \left(\frac{3\pi}{32 G\rho_0}\right)^{1/2} \qquad (2)$$

ρ_0 being the density of the gas at the centre. Calculations show that in a collapsing cloud, t_{cool} is much less than t_{ff} [76,77]. Thus isothermal collapse of the cloud and cascade fragmentation in it will prevail at temperature ~10 K until the gas attains the critical density of $\rho \sim 10^{-13}$ gm cm^{-3} [71–73], when the cloud becomes optically thick in the infrared and microwaves and starts trapping compressional heat produced by the collapse. The process of fragmentation then ceases. A group of protostars are thus formed out of the initial cloud through the process of what is called *the opacity-limited hierarchical fragmentation.*

Thus the opacity-limited hierarchical fragmentation of a dense cold molecular cloud leads to the formation of a group of protostars having a power-law mass distribution determined by the scale of the Jeans mass, $M_J \propto T^{3/2}\rho^{-1/2}$. The time period for the formation of these stars is of the order of the free-fall time for the cloud given by eq. (2). Since both the free-fall time and the Jeans mass are functions of the gas density which is different at different regions within the cloud, the stellar mass function as well as the time period for formation of stars will be different at different parts of the cloud. At the dense core of the cloud smaller mass protostars will be formed in larger numbers within relatively shorter time-scales. Calculations show that $t_{ff} \approx 3 \times 10^4$ years and M_J is very much smaller than the mass of the sun if $\rho \sim 10^{-18}$ gm cm^{-3} and $T \sim 10$ K [78]. Thus within the cold dense core of a cloud, a group of low mass stars can be formed within a time-scale of 10^5 years or so [59,71,78]. This time scale is much shorter than the stellar evolution time-scale on which the stars evolve, supernovae explode and gas dispersal takes place. The latter time-scale is of the order of 10^7 years [59,78]. Fragmentation occurs on scales exceeding the Jeans mass M_J when the optical depth $\tau_0 \simeq 1$. Calculations show that the first generation of fragments in the cold core of the clouds has masses in the range 0.01 – 0.1 $M_\odot$ [59,74]. Radiation from these fragments will raise the mean temperature of the outer infalling gas and a second generation of fragments will be produced with higher M_J upto 1 $M_\odot$. The process thus advances with subsequent generations of fragmentation with higher and higher Jeans masses in which smaller numbers of higher mass fragments will be formed [74]. Such a theory finds support in the observations of the Orion cloud. Observations in the Orion region suggest that recent formation of massive stars are predominantly confined to the outermost edge of the Orion molecular cloud. Also, the generation of fragmentation advancing from core to the boundary of the cloud takes place over longer and longer time-scales until the gas dispersal begins over the stellar evolution time-scale ($\sim 10^7$ years) [59,74–78].

The collapse is always highly non-homologous [45,59,71,73]. Even if the cloud possesses uniform density initially, the density distribution soon becomes strongly centrally condensed. The degree of central condensation increases at an ever accelerating rate leading to a runaway growth of a sharp central spike in the density distribution [71]. In the process, the rapidly collapsing central core of the cloud shrinks in size and mass. The bulk of the cloud mass is still left behind in a more slowly collapsing extended envelope of infalling matter whose size and mean density are still much the same as those of the initial cloud. The growth of the central density peak continues unhindered until the central density exceeds 10^{-13} mg cm^{-3}, the limit upto which the isothermal collapse can proceed [71,73]. The runaway growth of the central density can be understood by considering the free-fall time given in eq. (2) which is minimum where the density is maximum.

When the collapse gets well under way, significant changes in density occur progressively in smaller region at the centre on a gradually shorter time-scale. But in the bulk of the cloud occupying the outer parts which contains most of the mass, almost no change takes place. Here the density distribution closely approaches the law $\rho \propto r^{-2}$, which characterises all isothermal collapse calculations with spherical symmetry, irrespective of the details of the initial and boundary conditions [71,79–84]. On the other hand, in the inner core where the free-fall collapse prevails, the density law is $\rho \sim r^{-3/2}$ which is characteristic of the free-fall density distribution. However, with the onward progress of the collapse, more and more material falls at the centre and the region in which the distribution $\rho \propto r^{-3/2}$ prevails, expands outwards until it engulfs almost the entire cloud [59,71,79].

6. Gravitational collapse and fragmentation of gas clouds (Mathematical treatment)

6.1. Gravitational collapse : Jeans mass :

The principal mechanism of star formation is associated with the process of gravitational collapse. The collapse mechanism was first studied by Sir James Jeans in 1902. He considered a non-rotating, non-magnetic, homogeneous gas cloud in a state of equilibrium and assumed the presence of small one-dimensional local perturbation inside it. Let ρ_0 be the density of homogeneous cloud in equilibrium and $\rho_0 + \rho_1$ and v_1 be its density and velocity respectively in the perturbed state, where ρ_1, v_1 are small.

Equations of continuity and of motion in the perturbed state with the assumption that the square and product of perturbed quantities are negligible, are given by

$$\frac{\partial \rho_1}{\partial t} + \rho_0 \nabla \cdot v_1 = 0 \tag{3}$$

$$\frac{\partial v_1}{\partial t} = -\nabla\phi_1 - \frac{\nabla p_1}{\rho_1} \tag{4}$$

where p_1 and ϕ_1 are perturbed pressure and potential function of gas cloud satisfying the equations :

$$p_1 = \frac{KT}{\mu m_H}\rho_1 \tag{5}$$

and $$\nabla^2\phi_1 = 4\pi G\rho_1. \tag{6}$$

K, μ, m_H, G being respectively the Boltzmann constant, the mean molecular weight of gas, the mass of hydrogen atom and the gravitational constant; T the gas temperature.

From above equations we obtain the wave-equation :

$$\frac{\partial^2 \rho_1}{\partial t^2} = 4\pi G\rho_0\rho_1 + \frac{KT}{\mu_{m_H}}\nabla^2\rho_1 \tag{7}$$

whose solution is

$$\rho_1 = \rho_0 \exp\left[i\left(\frac{2\pi x}{\lambda} - \omega t\right)\right] \tag{8}$$

where $$\omega^2 = \left(\frac{2\pi}{\lambda}\right)^2 \frac{KT}{\mu_{m_H}} - 4\pi G\rho_0 \tag{9}$$

Here, ω is the frequency and $\frac{\lambda}{2\pi}$ the wave length of the propagating wave generated due to perturbation. The velocity V of small density perturbation wave is given by

$$V^2 \quad \frac{\omega\lambda}{2\pi} = s\left(1 - \frac{\lambda^2 G\rho_0}{\pi s^2}\right)^{1/2} \tag{10}$$

where $s = \left(\frac{p_0}{\rho_0}\right)^{1/2} = \left(\frac{KT}{\mu_{m_H}}\right)^{1/2}$

is the sound velocity.

For stability. λ as well as V should be real.

Thus if

$$\lambda > \lambda_J = s\left(\frac{\pi}{G\rho_0}\right)^{1/2} = \left(\frac{\pi KT}{\mu_{m_H} G\rho_0}\right)^{1/2}$$

$$\sim 6\times 10^7\left(\frac{T}{\mu\rho_0}\right)^{1/2} \text{ cm}, \tag{11}$$

the density perturbation will grow exponentially in time and the waves are unstable. λ_J is called *Jeans critical length*. Thus when the dimension of cloud exceeds Jeans critical length instability sets in and the cloud collapses to avoid the instability. The corresponding cloud mass, called *Jeans critical mass for gravitational collapse*, is given by

$$M_J = \frac{\pi}{6}\rho_0\lambda_J^3 = \frac{\pi}{6}\left(\frac{\pi KT}{\mu_{m_H} G}\right)^{3/2} \rho_0^{-1/2}$$

$$\sim 10^{23}\left(\frac{T}{\mu}\right)^3 \rho_0^{-1/2} \text{ gm} \tag{12}$$

Chandrasekhar [85] extended the collapse problem by introducing magnetic field and internal motion (or rotational velocity) of the cloud. Here, the kinetic pressure $\frac{1}{2}\rho_0 v^2$ and the magnetic pressure $\frac{1}{2}\rho_0 v_A^2$ are added with gas pressure $\frac{1}{2}\rho_0 s^2$ in the eq. (11) where $v_A^2 = \frac{H_0^2}{4\pi\rho_0}$ is the square of Alfvén velocity. Thus we get Chandrasekhar's critical length λ_c for collapse,

$$\lambda_c = \left(\frac{\pi}{G\rho_0}\right)^{1/2}\left[s^2 + \frac{1}{2}v^2 + \frac{H_0^2}{8\pi\rho_0}\right]^{1/2}$$

$$= \left(\frac{\pi K}{G\rho_0 m_H}\right)^{1/2}\left[\frac{T}{\mu} + \frac{m_H}{K}\left(\frac{1}{2}v^2 + \frac{H_0^2}{8\pi\rho_0}\right)\right]^{1/2} \tag{13a}$$

Substituting values of G, m_H, K we obtain Chandrasekhar's critical mass M_c for collapse as

$$M_c = \frac{\pi}{6}\rho_0\lambda_c^3 = 10^{23}\left[\frac{T}{\mu} + 10^{-8}(0.5v^2)\right.$$

$$\left.\frac{4\times 10^{-10} H_0^2}{\rho_0}\right]^{3/2} \rho_0^{-1/2} \text{ gm}, \tag{13b}$$

v is expressed in cm s^{-1} and H_0 in Gauss.

Comparing M_J and M_c we obtain that gravitational collapse is comparatively inefficient in rotating and/or magnetic gas cloud.

6.2. Fragmentation under free-fall collapse :

Now let us consider free-fall collapse of a gas cloud of mass M and initial radius R_0. At time t it collapses to a sphere of radius $R(t)$ given by the equation

$$\frac{d^2 R(t)}{dt^2} = -\frac{GM}{R(t)^2} \tag{14}$$

$R(t)$ is a decreasing function of t. It can be deduced by integration that collapse time t is given by

$$t = \quad 8G\rho_0 \quad \cos^- \quad + \in | \tag{15}$$

i.e. $t \propto \rho_0^{-1/2}$ where $0 < \in \leq \frac{1}{2}$.

Using mass conservation law, *viz*. $\rho R^3(t) = \rho_0 R_0^3$ we get the density of the gas in time t as

$$= \rho_0 \left(\frac{R_0}{R(t)} \right)^3 \quad \rho_0 \sec^6 \left[\sqrt{\frac{8\rho_0 G}{3}} t - \in \right] \tag{16}$$

At $t = t_1 = \frac{+ \in}{\sqrt{\frac{8G\rho_0}{3}}}$, we see $\rho \to \infty$ and $R(t_1) \to 0$.

Now eq. (15) shows that the collapse time decreases and consequently collapse rate increases when the gas medium is getting denser (as $t \sim \rho_0^{-1/2}$). So if the collapsing cloud is not absolutely homogeneous the denser region collapses faster. Also the stage $t = t_1$ is attained more quickly in the denser region. Therefore, when a gas cloud is collapsing the denser regions will collapse more rapidly and a time comes when the densities of these regions become enormously high. This generates extremely high internal pressure in these regions and as a result the gas in this regions will be split up into several fragments. Thus we get several fragmented gas blobs at the heart of the cloud which is also collapsing at slower rate. These gas blobs are the initial form of stars. Hoyle [86] suggested that fragmentation process can go on recurrently giving birth to clusters of stars from the parent cloud.

6.3. Radiative cooling in isothermal stage of fragmentation :

If heat generated by gravitational collapse cannot be radiated away, gas temperature gradually rises. As a result, internal pressure develops inside the cloud which prevents free-fall collapse. So in order to keep collapse and successive fragmentation process efficient the process of radiative colling is needed. The cooling time t_{cool} is proportional to ρ^{-1} whereas the free-fall time t_{ff} is proportional to $\rho^{-1/2}$ (Eqs. 1 & 2). ρ being the gas density.

Thus $\frac{t_{cool}}{t_{ff}} \sim \rho^{-1/2}$.

At lower density, $\frac{t_{cool}}{t_{ff}} \geq 1$

Therefore the compressional heating rate is higher than that of radiative cooling. Eventually the cloud will heat up and collapse is prevented. In extreme case the cloud may even dissipate. Goldsmith and Silk [87] suggested that :

(i) If $t_{cool} > H_0^{-1}$, the age of the universe, the gas cloud cannot cool and evolve.

(ii) If $H_0^{-1} > t_{cool} > t_{ff}$, the gas cloud cools but cannot radiate away the compressional heat within freefall time. Adiabatic collapse then takes place and slow opacity-dominated collapse follows.

(iii) If $t_{cool} < t_{ff}$, isothermal collapse occurs leading to fragmentation.

6.4. Opacity-controlled star formation :

The present clouds from which stars are born, pass through three different stages :

(i) Diffused phase with number density $n < 10^3$ cm^{-3}.

(ii) Isothermal or transparent phase with $10^3 < n < 10^{12}$ cm^{-3}.

(iii) Adiabatic phase with $n > 10^{12}$ cm^{-3} and the cloud is opaque.

It has been shown that the isothermal collapse *i.e.* collapse with dissipation of heat is necessary for successive fragmentation. But this process cannot continue ceaselessly. Gradually fragments become denser and more opaque to trap heat within their interior. This heat generates internal pressure which opposes further collapse and fragmentation. The process of star formation is then controlled by opacity.

Optical depth

The opacity of a gas cloud is measured by its optical depth T_ν given by

$$T_\nu = \int^{L} \alpha_\nu dx \tag{17}$$

where L is the thickness of the cloud and α_ν is absorption co-efficient for radiation with frequency ν per unit length. If $T_\nu << 1$ the cloud is transparent or optically thin to the light of frequency ν. T_ν increases as the cloud becomes more and more opaque. Molecules and dust grains play an important role to enhance opacity of the cloud.

In case of silicate grains, the optical depth is given by

$$T_\lambda = 0.4 \left(\frac{n_{H_2}}{10^{12}\,\text{cm}^{-3}} \right)^{1/2} \left(\frac{T}{30\ \text{K}} \right)^{5/2}. \tag{18}$$

This shows that the cloud temperature T and number density of hydrogen molecule n_{H2} are responsible to enhance its opacity.

Adiabatic phase

In an adiabatic phase gas pressure plays an important role to prevent free-fall collapse. Jeans mass M_J is then given by

$$M_J \sim T^{3/2}\rho^{-1/2} \sim \left(\frac{p}{\rho}\right)^{3/2}\rho^{-1/2} \sim \left(\rho^{\gamma-\frac{4}{3}}\right)^{3/2}$$

$$\left[\text{As } p \sim T\rho \sim \rho^{\gamma}\right].$$

For the isothermal stage $\gamma < \frac{4}{3}$, hence M_J decreases as density increases *i.e.* as collapse proceeds. Therefore, efficiency of collapse increases as collapse progresses. In adiabatic stage $\gamma > \frac{4}{3}$, so M_J increases with increase in density. Hence collapse itself prevents the efficiency for further collapse and the process of successive fragmentation stops at a certain stage. The variation of M_J with temperature in isothermal as well as adiabatic phase has been shown in Figure 2 [88].

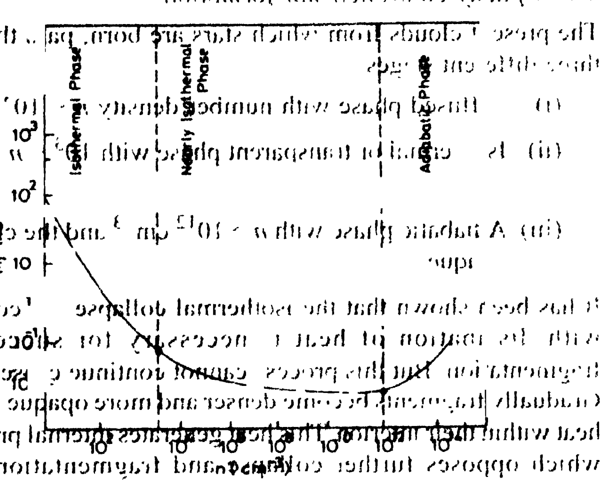

Figure 2. Relation between the gas density and Jeans mass

In nearly isothermal phase, we assume that heat gained by gas compression in a cloud is just radiated away. The cooling rate in this case is given by [89],

$$\Lambda_g = 4\sigma T_g^4 Q_p(Tg, a)\,\sigma_g n_g, \tag{19}$$

where $Q_p(Tg, a)$ is Planck mean absorption cross section per grain of radius a, temperature T_g, n_g being the number density of grain in the cloud; σ_g is the cross section of the grain, σ is Stefan-Boltzmann constant. The rate at which compressional energy is gained is given by

$$\Gamma = \frac{\rho K T_g}{\mu}\frac{d}{dt}\log\rho \tag{20}$$

and $\frac{1}{3}\frac{d}{dt}\log\rho$ is the rate of collapse. Using condition for near isothermal collapse, *viz.*

$$\Lambda_g = \Gamma c,$$

similarity solution yields [90]

$$\frac{d}{dt}\log\rho = (16\pi\rho G)^{1/2} \tag{21}$$

In free-fall collapse, we have

$$\ddot{r} = -\frac{GM}{r^2},$$

giving

$$\frac{d}{dt}\log\rho = \sqrt{\frac{3}{2}}(16\pi\rho G)^{1/2} \tag{22}$$

Eqs. (21) and (22) indicate that collapse rate is decreased when pressure is introduced.

In adiabatic stage when fragments are optically thick, the radiation rate is

$$Lg = \frac{4\pi r^2\sigma T^3}{K_r}\frac{dT}{dr}\ \text{erg s}^{-1} \tag{23}$$

K_r is Rosseland mean opacity in cm^{-1} [89].

When r is half the cloud radius R and $T_{1/2}$ is half the central temperature, we obtain

$$L_g = 0.4\ \sigma T_{1/2}^4 (K_r)^{-1}\left(\frac{m}{\rho}\right)^{\frac{1}{3}} \tag{24}$$

m and ρ being mass and density of the cloud. Eq. (24) shows that cooling rate in adiabatic stage depends on the cloud mass while that in isothermal stage, is independent of mass of the cloud [see eq. (19)]. Thus massive almost opaque fragments cool faster and undergo further fragmentation while less massive opaque fragments collapse quasistatically avoiding further fragmentation. Gaustad [91] suggested that opaque fragments of mass < 0.2 $M_\odot$ possess slow quasistatic near free-fall collapse until they acquire the density of stars. Thus, low mass fragments are directly affected by opacity. Massive fragments are much more governed by gravity. They continue near free-fall motion inspite of opacity and are broken into less massive pieces before being controlled by opacity. When temperature rises to nearly 2000 K, grains are evaporated and molecules are dissociated. This removes opacity of the cloud to some extent, triggering near free-fall collapse until the cloud attains nearly stellar density.

6.5. *Fragmentation of clouds, formation of first and second generation stars*

When a gas cloud collapses, generally the denser regions which collapses much faster give birth to a number of protostars. The fractional mass of the cloud going into these stars is very low. The remaining portion of the cloud which contains most of the cloud mass continues to collapse much slowly. Now, energy emitted by the stars already formed within the cloud, can be uniformly distributed throughout

is non-magnetic

(see Section 9). Thus when star formation takes place in this region of higher temperature, the new-born second generation stars would be comparatively more massive. Of course, the number of stars formed in this region, is much lower than those in the denser regions.

6.6 Fragment mass :

According to Silk [92a] the process of collapse and consequently of fragmentation is associated with the characteristic mass M_c of a fragment and Kelvin-Helmholtz contraction time t_{KH},

$$\text{where } M_c = 20(T/10^4)^{5/6} \, M_\odot \tag{25}$$

$$\text{and } t_{KH} \approx GM^2/RL$$

$$\approx 2 \times 10^7 (M/M_\odot)^2 (L_\odot/L)(R_\odot/R) \text{ year} \tag{26}$$

[Long, 92b]

M is the mass of the fragment and L its luminosity.

When $M = M_c$, a slow luminosity controlled Kelvin-Helmholtz contraction takes place.

When $M < M_c$ the collapse is quasi-hydrostatic with rare chance of fragmentation.

When $M > M_c$, dynamical collapse continues leading to fragmentation. Larger M_c occurs at higher temperature producing massive protostellar fragments.

According to Hutchins [93], super-massive stars should form in the earliest epoch of the universe. In this period H_2 is produced by negative hydrogen ions. At $T \sim 1800$ K and $\rho \sim 10^{-18}$ gm cm^{-3}, most of the hydrogen molecules are dissociated through collisions. Hence due to lack of cooling agents massive ($\sim 500 \, M_\odot$) fragments are produced. But Silk proposed that disappearance of H_2 makes the gas almost transparent. This leads to dynamical collapse and fragmentation, so massive fragments would be broken into pieces. Also L_α cooling process which is operative at $T \sim 10^4$ K, will reduce the mass of the fragment to the order of $0.2 \, M_\odot$ to $0.3 \, M_\odot$. Massive fragments in L_α-radiation bath are probable provided the fragments continue to collide and generate internal motion. This heats up gas to counter balance L_α cooling. Also heating enhances ionization fraction which is exponentially proportional to temperature. The opacity of the fragment which is proportional to ionization fraction will increase subsequently giving a check for further fragmentation.

7. Mass function of stars and star formation efficiency (SFE)

When a group of stars form out of a cloud, they form with different initial masses. This fact leads to the study of the mass function of stars.

(i) *The present day mass function* $\phi_{ms}(\log M)$ of stars in the solar neighbourhood means the number of main sequence stars per logarithmic mass interval per square parsec in the galactic disk in the solar neighbourhood over the entire gas column perpendicular to the galactic disk.

The initial mass function $\xi(\log M)$ of stars is defined as the total number of stars (main sequence stars as well as others) that have ever formed per unit logarithmic mass interval per square parsec in the galactic disk over the entire gas column normal to the disk.

The initial mass function (or IMF) can be derived by two steps :

(i) From the knowledge of luminosity function one can determine the present day mass function (or PDMF) and

(ii) Then considering birth rate of stars and PDMF the IMF can be ascertained [94].

The luminosity function $\phi(M_v)$ is the number of stars of all types per unit absolute magnitude per cubic parsec in the galactic plane. We can derive the present day mass function (PDMF) ϕ_{ms} from the luminosity function $\phi(M_v)$ by using the transformation law [105]:

$$\phi_{ms}(\log M) = 2\phi(M_v) \left| \frac{dM_v}{d \log M} \right| H(M_v) f_{ms}(M_v) \tag{27}$$

where H is the scale height of gas which can be obtained by integrating luminosity function over the entire gas column perpendicular to the disk. f_{ms} is the fraction of main sequence stars. McCusky [95] and Wielen [96] have plotted $\phi(M_v)$ against M_v and showed that $\phi(M_v)$ increases with M_v in the absolute magnitude range $-3 \leq M_v \leq 15$. Outside this range the luminosity function is uncertain since highly massive stars (with $M_v \leq -3$) are very rare and extremely faint stars ($M_v \geq 15$) cannot be detected properly. They also concluded that the number density of stars decreases with increase in luminosity.

Now knowing the luminosity function one can determine PDMF of a group of stars provided the scale height H and fraction f_{ms} of main sequence stars are known.

To proceed to the next step, one can determine how PDMF, IMF and rate of star formation are correlated. Miller and Scalo [94] have derived the correlation as

$$\phi_{ms}(\log M) = \frac{\xi(\log M)}{T_0} \int_{t_0 - t_{ms}}^{T_0} b(t)\,dt, \quad T_{ms} < T_0 \tag{28}$$

$$= \frac{\xi(\log M)}{T_0} \int_0^{t_0} b(t)\,dt, \quad T_{ms} \geq T_0 \tag{29}$$

where $b = b(t)$ is the birth rate of the stars of a specified group, T_0 is the age of the galaxy and T_{ms} is the main sequence life span of these stars. Eq. (28) holds for massive stars whose main sequence life span is shorter than the age of the Galaxy. Eq. (29) deals with low mass stars whose life span equals or even exceeds the age of the Galaxy.

In this case, PDMF and IMF are equal *i.e.*

$$\phi_{ms}(\log M) = \xi(\log M)$$

$$\text{and consequently } \int_0^{t_0} b(t)\,dt = T_0$$

Different expressions for star formation rate $b(t)$ have been derived by different authors *viz.*

Salpater [97], Schmidt [98], Rana [99], Dopita and Ryder [100] *etc*.

Knowledge of PDMF and $b(t)$ and use of (28) & (29) determine IMF of stars as function of their logarithmic mass. It can be shown that IMF decreases in power law as the stellar mass increases. This implies that low-mass stars are more abundant than the massive stars.

The same conclusion can be derived from Bhattacharyya and William [101]. We have

$$\frac{dN}{dM} \propto M^{-(1+x)}, \quad x > -1 \tag{30}$$

where N is the number of stars in the mass range (M, $M + dM$). x is called the slope of the IMF. Different values of x has been suggested by different authors.

$$\left.\begin{array}{ll} \text{According to Salpeter,} & x = 1.35 \\ \text{Scalo [102] gives} & x = 1.7 \end{array}\right\} \text{when } M > M_\odot.$$

when $M < M_\odot$, x has been taken to be 0.7 by these authors.

Basu and Bhattacharyya [103] have taken $x = 2.3$ for general mass range. Basu and Kanjilal [104] obtained $x \simeq 1$ for spherical cloud collapse. Robin and Crézé [105] showed that x lies between 1.8 to 2.2 in the mass range 1-3 $M_\odot$, provided star formation rate remains constant. Twarag [106] suggested very steep IMF with $x \sim 3$ in intermediate mass range.

Scalo [102] proposed that uncertainty is caused in determination of IMF due to uncertainty in determining nature of star formation rate (SFR) and the scale height for exponential law of stellar density perpendicular to galactic disk. The uncertainty in IMF ranges from 20 – 30% for $M < M_\odot$. When $M > M_\odot$ the uncertainty develops by the factor of 5 - 10. Observing IMF in solar neighbourhood Scalo [102] suggested that the slope of IMF is 2 – 2.2 if star formation rate is assumed to be constant and it ranges from 2.6 – 2.9 if star formation rate is taken to be increasing with time. When star formation rate decreases with time we get bimodel IMF with modes at $M \approx 0.3\ M_\odot$ and 1.1 – 1.3 $M_\odot$. It is generally accepted that SFR is either constant or slightly increasing with time.

Next let us discuss some aspects of star formation in the disk of the galaxy. The characteristics of disk stars depend on several parameters *viz*. colour, age, luminosity and spatial distribution. According to Haywood [107] the rate of star formation in the galactic disk follows the exponential law.

$$\text{SFR} \sim \exp(-t/\tau), \tag{31}$$

where τ has been generally taken as ± 5 GYr. The value of τ is valid throughout the age of the galactic disk.

Considering star count near the Galactic pole, Robin and Crézé [105] and Haywood *et al* [108] suggested different possibilities for the nature of star formation rate :

(i) SFR follows exponentially increasing law with variation factor 7 throughout the galactic age.

(ii) constant SFR.

(iii) exponentially decreasing law for SFR with amplitude 3.5 or 7.

(iv) Gaussian law for SFR with plausible amplitudes 3.5 or 7.

The star count in the Galactic pole indicates that the star formation rate in the first half of the period of evolution of the galactic disk has not attained its maximum value. So constant or increasing star formation rate should be acceptable. This requires recycling of gas into the galactic disk. Infall of gas from halo to disk is one of the mechanisms of mass replenishment. Average infall rate has been estimated to be about 3.5 $M_\odot$ pc^{-2} Gyr^{-1}. It was proposed by Robin and Crézé [105] and Haywood *et al* [108] that when mass of the star exceeds 1 solar mass about 26 – 46% of recycling of gas takes place.

Haywood *et al* [108] calculated the variation in percentage of re-cycling for different values of the slope of IMF. This is given by :

39 percent for the slope $x = 1.5$,

24 percent for the slope $x = 2.0$

44 percent for the slope $x = 1.35$ (Salpeter Slope).

Another formulation of SFR is given by

$$\left.\begin{array}{l} \text{SFR} = \nu\Sigma^{n} \\ \text{when } \nu = -\dfrac{1}{T_0}\log\mu s \end{array}\right\} (\Sigma \text{ is total surface density}) \tag{32}$$

and $\mu_s = \dfrac{\text{Surface density } \Sigma_g \text{ of gas}}{\text{Total surface density } \Sigma}$. [108]

If $T_0 \sim 10$ Gyr,

$$\nu = (0.13 - 0.2)\ (\text{Gyr.})^{-1}. \tag{33}$$

All these discussions are confined for disk stars. Stars belonging to thick disks are unusually faint. Therefore, they are practically undetectable and consequently beyond the scope of investigation.

8. Efficiency of star formation and its evolution

While studying the characteristics of star formation one should consider an important parameter, *viz*., efficiency of star formation. This is the ratio of the stellar mass to the total mass (including gas and star) of the cloud where stars are born.

$$\text{The efficiency } \zeta = \frac{M^*}{M^* + M_{gas}} \tag{34}$$

M^* and M_{gas} are masses of stars and gas respectively within the cloud [109]

Wilking and Lada [47] estimated that when the efficiency of a star cluster exceeds 50 percent it becomes gravitationally bound. We know that the protostars and brown dwarfs are formed within the collapsing gas cloud as a result of fragmentation. Initially low mass stars and brown dwarfs are formed in large numbers in the central core of the cloud but the total mass involved in the process is not a large fraction of the cloud mass. Gradually star formation is propagated outwards as the collapse proceeds and stars of higher masses are formed. When the star formation process is completed within the cloud we get what is called the initial mass function (IMF). The total mass used in stars then yields what may be called the initial star formation efficiency (or the initial SFE). That SFE will subsequently further evolve in time as the stars accumulate more mass by accretion from the surrounding envelope or by mutual collisions. Mutual collisions both sticking as well as breaking will also change the IMF. Thus after initial completion of fragmentation of cloud, both IMF and SFE evolve till the cloud disruption takes place in the evolution time-scale of massive stars ($\sim 10^7$ years).

8.1. Minimum mass of stars :

In the isothermal gas medium the process of successive fragmentation continues yielding smaller and smaller fragments. Fragmentation stops when radiative cooling becomes inefficient and the parent cloud becomes opaque enough to trap heat inside it. Then we obtain the gas blobs which are the most primitive form of stars. So in order to obtain low mass stellar blobs the radiative cooling process should be effective. Kanjilal and Basu [104] computed minimum mass of opaque stellar blobs in the presence of different types of grains within the cloud. The masses are found to vary from 0.003 to 0.007 $M_\odot$ depending on the nature of the grain. According to Low and Lynden Bell [110] this is about 0.007 $M_\odot$. Computation of Silk [89] yields minimum fragment mass to be about 0.005 $M_\odot$. Basu and Bhattacharyya [103] found them within the range of 0.001 to 0.003 $M_\odot$. Thus the minimum mass of stellar blob in its initial stage is far less than 1 percent of the solar mass. These bodies will grow gradually by accreting mass from the parent cloud or by sticking collisions and SFE will increase consequently.

8.2. Mechanism for mass accretion :

There are several processes by which smaller stellar blobs acquire mass and grow more massive.

Larson's model [90]

This model represents a gas cloud with a group of primitive stars inside it. Initially the gaseous envelope is much more massive than its stellar counter part. But as the star forming region is more dense, the gas envelope is attracted by the gravitational pull of this region and ultimately falls on to it. The stellar blobs consume this infalling mass and gradually grow massive. According to Spitzer [111], the mass accretion rate is given by

(34)

$$\frac{dM}{dt} \; 4\pi\rho(GM)^2 \qquad (35)$$

ρ and v_1 being density and velocity of accreting material at infinity.

As gas is consumed by stars, the density of gas within the cloud changes with time. Ghose *et al* [112] suggested an expression for the density as

$$\rho \sim A(t) r^{-\alpha}, \qquad (36)$$

where $A(t)$ is a decreasing function of time, r the distance of gas particle from the cluster centre and $1 < \alpha < 3$. It was suggested that the amount of mass accreted by stars depends significantly on the exponent α. Lower the α higher is the mass accreted by stars. If α is close to 3 the process of accretion is rather inefficient. Basu and Bhattacharyya [103] suggested another mechanism for accretion of mass by protostars. They proposed that protostars pickup mass continuously when they move at random through the cloud of gas which they populate. A protostar of radius λ passes through a volume $\pi\lambda^2 ds$ of the cloud in time dt and picks up a fraction f of cloud mass. Therefore the accretion rate is

$$\pi\lambda^2 \rho f v, \qquad (37)$$

ρ being the density of gaseous medium and v the random speed of the blob. They have computed the time by which a star blob becomes ten times massive. The time scale spans 10^5 to 3×10^7 years depending on the choice of the fraction f.

Protostars grow massive not only by accreting mass from the surroundings but also by the process of inelastic collisions among themselves [113]. These collisions are possible provided collision time is shorter than the free-fall time of gas. Now

$$\frac{t_{coll}}{t} = (7.8)\times 10^4 \left(\frac{T/10K}{\mu/2}\right)^{7/2} \frac{R^{7/2}}{N^{3/2}(m_{av})^{7/2}\left(H\frac{m}{m_{av}} \quad \frac{m}{m_{av}}\right)}$$

[113]. (38)

Here, R is the radius of the cloud in parsec, m is the mass of the protostellar fragment and m_{av} is the average mass of the fragment in the clusber (both are expressed in $M_\odot$). $\frac{t_{coll}}{t_{ff}}$ has been shown to be highly sensitive on $\frac{m}{m_{av}}$.

$$\text{If } \frac{m}{m_{av}} \ll \quad \frac{t_{coll}}{t_{ff}} \propto \left(\frac{m}{m_{av}}\right)^{-1}$$

Hence collision is found to be more frequent for high mass fragments.

8.3 Upper limit of stellar mass :

If the growing stellar blob possesses mass in excess of a critical value the accretion process continues throughout its evolutionary phase until it is blown up as a supernova.

According to Larson and Starfield [114], the upper limit of the stellar mass depends on the initial cloud temperature. For cloud with initial temperature ranging between 10 K – 20 K, the upper limit of the stellar mass should lie between 60 – 120 $M_\odot$.

When protostars are formed within a cluster they remain embedded in a dark envelope of thick gas and dust. Luminosity of stellar objects is absorbed by dust and is re-radiated in infrared rays. The ray heats up the outer part of the cloud, where most of the gas still exists in the cloud. Heat generates pressure force which tends to oppose gravitation. As a result infall of cloud mass on to protostars slows down and ultimately stops. Larson [90] has given an estimate for pressure to gravity ratio as

$$\frac{\text{pressure}}{\text{gravity}} \quad \frac{\frac{1}{\rho}\frac{dp}{dr}}{GM} \quad 0.54\left(\frac{M}{M_\odot}\right)^{0.24} \tag{39}$$

M being the mass of the star blob. When M ~ 60 M⊙, pressure becomes predominant and collapse of the outer layer of the protostar halts, or even materials in this region disperse. Moreover, stellar wind is generated by a protostar when it is 10^4 years old. The wind drives away surrounding mass at the rate of about 10^{-5} - 10^{-6} M⊙ per year. The velocity of outflow of mass is about several hundred kilometers per second. (Rate of outflow of mass by solar wind is about 10^{-14} M⊙ per year). Also for massive stars radiation pressure plays more vigorous role than stellar wind in order to drive material from the stellar surface.

$$\frac{\text{Radiation pressure}}{\text{Dynamical pressure}} \simeq 2 \times 10^{-5}\left(\frac{M}{M_\odot}\right)^{17/5}. \tag{40}$$

Thus for a massive star radiation pressure is so high in comparison with dynamical pressure the down fall of mass on to the star is totally inhibited. Even sometime the portion of the outer layer of the star is blown away by enormous radiation pressure of the star. Therefore the mass of a star cannot exceed a critical limit which depends on the assumed conditions.

9. Parameters associated with star formation process

How does the star formation process in a gaseous medium remain active ? The star formation process mainly requires instability in a gas medium. If for a gas cloud the Jeans mass M_J (or more generally Chandrasekhar's mass M_C) is small, then even smaller gas clouds suffer instability and collapse. On the other hand, large M_J (or M_C) ensures stability of even larger clouds and the oportunity of star formation is reduced. Thus smaller M_J (or M_C) in a gas cloud indicates most favourable condition for star formation. M_C is associated with several parameters, *viz*., density ρ, temperature T of gas, the gas velocity V and its magnetic field strength H. These parameters should have significant influence on the intensity of star formation episode.

9.1. *Effect of density on star formation :*

We find from eq. (13) that M_C decreases as the density ρ of the gas medium increases. Therefore, star formation process becomes more vigorous in denser medium and star formation is triggered when the gas cloud is compressed to some critical values by some mechanical processes. Shock waves generated by expanding H II regions are found to trigger star formation in several galaxies *viz*. M17, M42, NGC 281, W3 *etc*. [115]. Blast wave generated due to supernova outburst also causes formation of metal rich population I stars. Bright young stars are often observed in spiral arms of galaxies. These are caused by density wave shock developed in these regions. Cloud-cloud collisions also produce strong shocks and create favourable conditions for star birth [116].

Explosions in the nuclei of active galaxies generate strong shock waves. This enhances star formation activities in the central region of galaxies to a great extent. Saha *et al* [117] showed that galactic nuclear explosion enhances external pressure surrounding the gas cloud. This reduces Jeans mass and triggers star formation. Also as a result of galactic nuclear explosion, gas is pushed away from the galactic centre Expelled gas loses its angular momentum after moving through certain distance from the centre. It then returns towards the centre. The collision between outgoing and incoming gas creates a compressed layer triggering burst of star formation [118]. Interaction between galaxies and their merger produces compression which leads to burst of star formation. It has been found that most of the star burst galaxies are interacting and/or merging galaxies [119,120]. High star-forming activities have also been observed in galaxies with strong bars. Generally bar formation in a galaxy takes place when two or more galaxies merge together. As the bar forms, the bar axis b/a decreases and as a result, gas is pushed into the central region causing formation of bulk of stars in the central zone [121–123].

9.2. *Cloud temperature and star formation :*

Jean's critical mass decreases as the temperature is lowered. Therefore cool clouds are more suitable for star formation. Cooling is possible in the presence of (1) metals (2) molecules and (3) grains. Metals are actually formed inside stars in course of stellar evolution. Mass shed-off by evolved stars and supernova outbursts carry away the metal contents to the interstellar medium. Metals in gas cloud, lower the cloud temperature and keep it suitable for efficient star formation. Molecules of hydrogen and carbon also lower the cloud temperature to the range 10°K – 300°K through infrared and microwave transitions. Grains of silicates, ices *etc*. are formed from metal components. These serve as efficient coolants for the star forming clouds.

9.3. *Magnetic field and star formation :*

Turbulent motion and magnetic field increase the value of Mc and therefore reduce the efficiency of star formation. But the magnetic field plays a very complex role in star formation mechanism. This has been studied by several authors, *viz*., Mestel [124], Mouschovias [125], Silk [88], Umebayashi and Nakano [126] *etc*. Actually, collapse and fragmentation of magnetised gas cloud have been found to depend on the shape of the cloud and also on the structure of the magnetic field. In this connection, the following cases may be noted :

(i) *Collapsing cloud is spherical :*
Conservation of mass and magnetic flux gives respectively $\rho \sim r^{-3}$ and $H \sim r^{-2}$ *i.e.* $\frac{H^3}{\rho^2}$ constant.
If the cloud is non-rotating and gas pressure is negligible, Mc ~ $\frac{H^3}{\rho^2}$ and therefore remains same for all densities. Fragmentation cannot take place in this case.

Consider spherical magnetic cloud of mass $M_\odot$, radius R_0 and initial magnetic field H_0. Assuming that kinetic and thermal energy of gas are inappreciable in comparison with its gravitational and magnetic energy and using conservation of magnetic flux one can obtain the Virial theorem

$$\frac{1}{3} H_0^2 R_0^4 \left(1 - \frac{R}{R_0}\right) - \frac{3GM^2}{5} = 0 \tag{41}$$

or,
$$M_F^2\left(1 - \frac{R}{R_0}\right) - M^2 = 0 \tag{42}$$

where
$$M_F^2 = \frac{5}{9}\frac{H_0^2 R_0^4}{G} \tag{43}$$

If $M = M_F$, above equations yield $R = 0$. Otherwise if L.H.S. of eq. (42) remains negative, collapse continues upto $R \to 0$. If $M < M_F$, the left hand side of (42) remains negative provided $R > R_0 \left(1 - \frac{M^2}{M_F^2}\right)$ and collapse halts when $R = R_0\left(1 - \frac{M^2}{M_F^2}\right)$. If $M > M_F$, the left hand side of eq. (42) is always negative and magnetic field cannot prevent collapse. When mass of the cloud is greater than or equal to M_F collapse is possible despite the presence of the magnetic field. Evidently, M_F does not depend on the density of the gas cloud but depends on the magnetic field strength H_0. As in this case, the collapse does not depend on density, fragmentation does not occur within the collapsing cloud.

(ii) *Collapsing cloud is a prolate spheroid with the magnetic axis along the major axis :*
The gas in the form of prolate spheroid has a tendency to take cylindrical shape. Hence for conservation of mass $\rho \propto r^{-2}$. This, with conservation of magnetic flux yields $H_0 \propto \rho$. This gives

$$M_c \sim \frac{H_0^3}{\rho^2} \sim \rho.$$

Hence, M_c increases with density and fragmentation is impossible.

(iii) *Collapsing cloud is an oblate spheroid with magnetic axis as minor axis :*
In this case the flow of gas is along the magnetic axis and ρ does not depend on H_0. Hence $M_c \sim \rho^{-2}$ and decreases as density increases. This leads to collapse and fragmentation. As the collapse rate has been reduced by the magnetic field, fragmentation takes place when the cloud becomes sufficiently flattened.

Magnetic braking : Rotating magnetic cloud.

Though magnetic field opposes the process of star formation it indirectly plays an important role in favour of star formation mechanism in a rotating gas cloud. Rotation generates centrifugal force which tends to oppose gravitational collapse. If ω is the angular velocity of gas, the centrifugal force F_θ on a particle of unit mass at a distance r from the centre is given by

$$F_\theta = \omega^2 r.$$

If angular momentum is conserved $\omega \sim r^{-2}$, giving $F_\theta \sim r^{-3}$, whereas the gravitational pull ~ r^{-2}. Hence in the central region of collapsing cloud, centrifugal force increases more rapidly than gravitational pull. Thus, collapse process becomes more and more inefficient in the central region of the cloud. This prevents occurrence of fragmentation in this region.

If magnetic field has a component perpendicular to the angular momentum vector, it will tend to remove non-uniformity of rotational velocity within the cloud. Then the centrifugal force becomes ~ r^{-1}, which would not be as important as gravity in the central region. Moreover, magnetic field lines establish a link with the surrounding cloud and transports angular momentum outwards. This removes the problem raised by the centrifugal force specially in the central region of the cloud. If magnetic field is perpendicular to the axis of rotation, braking process is very active and redistribution of angular momentum takes place in a time scale ~ 10^6 years which is shorter than free-fall time [127]. If magnetic field is parallel to the rotation axis braking time is about 5 times longer than that in the perpendicular case [127].

Magnetic field in the presence of plasma and dust grains.

Mestel and Spitzer [128] have studied the nature of magnetic field in partially ionized gas. Let us consider an ionized gas cloud where magnetic field is just sufficient to balance gravitational pull. Neutral gas is pulled towards the centre of the cloud while ionized gas is drifted outwards. As a result a frictional force develops between ionized and neutral components of gas. Magnetic flux is counteracted by the frictional force and is dissipated away continuously.

The presence of dense dust grains in magnetised ionized gas cloud also produces a peculiar effect [126]. Dust grains in dark clouds contain negative charge. Thus the drift produced by dust grains controls magnetic flux loss caused by ion drift and lengthens the flux loss time scale. It has been estimated that when density of gas is about 10^9 particles cm^{-3} flux loss time exceeds 10^6 years. Thus the problem of collapse and fragmentation of magnetised ionized gas in the presence of sufficient amount of dust grains is rather complicated. Magnetic field also plays another role supporting the process of star formation. It prevents penetration of cosmic ray into the gas and protects the gas from being over heated by cosmic ray. Thus gas remains comparatively cool and keeps Jeans mass (or Chandrasekhar's mass) for collapse smaller. As M_C is increased by the presence of magnetic field [eq. (13)], magnetised gas clouds give birth to massive stars though the number of stars produced are smaller and they are formed on a longer time-scale.

10. Star formation and the problem of baryonic dark matter

In course of our discussions in this review we had several occasions to mention about the dark matter. We are concerned here with only the baryonic part of the dark matter, the nonbaryonic part being out of context in our present discussions.

Different types of observations on our own Galaxy, the external galaxies and the clusters of galaxies, present compelling evidences that most of the matter in the Universe, near and far, remains hidden from our view. This matter is *hidden* because we *cannot detect* it by recording any kind of electro-magnetic radiation emitted from it. We can infer about its existence only by observing its gravitational pull produced on the visible matter around it. All observations and calculations indicate that at least 80 percent of the total matter remains invisible to us. This gives rise to the great problem of dark matter in astronomy. The question now is, in what form and physical state can this matter exist?

Astronomers have extensively pondered over the question for a suitable answer, Their speculations resulted in laying fingers upon such objects as the black holes, the dead stars such as the white dwarfs, neutron stars and population III stars, and the substellar objects like brown dwarfs and Jupiters. We will now show that the brown dwarfs and Jupiters which form in large numbers during the events of star formation are the most important candidates for resolving the problem of dark matter.

Some astronomers believe that a massive black hole ($M \sim 10^6$ M$_\odot$) resides at the centre of each normal galaxy. Also, there may exist a sparse distribution of black holes of stellar masses in a galaxy. But the existence of a significant part of the invisible mass in the form of black holes is very hard to realise. Detailed calculations on the numbers of white dwarfs and neutron stars in our Galaxy [129,130] have indicated that at most 20 percent of the total invisible matter may be deposited in these dead stars in our Galaxy.

Let us now consider the case of substellar objects, *viz.*, the brown dwarfs and Jupiters, that are believed to form in large numbers during the events of star formation from massive molecular clouds. It has been already discussed (Section 5) that the opacity-limited hierarchical fragmentation of a cloud leads to the production of a group of protostellar bodies having a power-law mass distribution of the form [30] where the index x has in general the range $1 < x < 2$. The form of the mass function shows that the number of bodies steeply increases as the mass decreases. There is no theoretical basis to assign a cut-off mass at the lower end that corresponds to $(M_J)_{min}$. The minimum Jeans mass has been variously determined by authors [89,103,104,110]. It can be as low as 0.005 M$_\odot$ or even less [104,129,130]. On the other hand, stellar evolution theory predicts that a body cannot attain the thermal balance unless its mass is $\geq$ 0.08 M$_\odot$. That is, such a body will fail to ignite its hydrogen fuel at the centre, and so it will not be able to achieve a stellar career. Thus the very large number of fragments that form having the mass range 0.002 M$_\odot$ < M < 0.08 M$_\odot$ during the event will be deposited as substellar objects, and as such, will contribute to the invisible mass. Various calculations have shown that nearly half of the total mass of the parent cloud can be locked in this way in substellar objects thus forming the dark matter [129–133,104] in any normal galaxy.

Thus, substellar objects appear to be the most important contributor to the baryonic dark matter that are simultaneously formed with the formation of normal luminous stars. The black holes and dead stars are likely to play more minor roles in this matter. On the other hand, the substellar objects are believed to be the dominant contributors to the massive dark halos of individual galaxies and the missing mass in clusters of galaxies.

11. Conclusions

(i) Massive, cold and dense molecular clouds form due to various types of instability in different regions of the galactic disk which is pervaded by interstellar matter.

(ii) The cloud collapses under self-gravitation maintaining isothermal collapse condition until the critical density ($\simeq 10^{-13}$ gm cm^{-3}) is attained.

(iii) Whatever be the initial and boundary conditions of the collapsing cloud, the collapse finally becomes highly non-homologous, leading to a rapid build-up of a high central density.

(iv) Opacity-limited hierarchical fragmentation of these clouds gives birth to a group of protostars of various masses having a power-law mass distribution.

(v) Low mass stars first form in large numbers at the central dense region of the cloud in a time scale of $\sim 10^5$ years. Star formation process is then propagated in the cloud outward forming subsequently stars of larger masses over longer time scales.

(vi) Magnetic field, if present in the cloud, may greatly influence the process of star formation.

(vii) Large numbers of fragments form in the event at the lower end of the mass range. The fragments having masses $\leq$ 0.08 M$_\odot$ fail to emerge as luminous stars and live as substellar objects. These objects form a significant part of the dark matter in a galaxy.

(viii) Under various parameter values, as much as half the parent cloud mass may be converted in the process to the substellar objects forming dark matter.

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